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RESEARCH MEMORANDUM

INVESTIGATION OF INTERNAL REGENERATIVE FUEL-HEATING SYSTEM FOR 20-INCH RAM JET

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation was conducted to evaluate the effectiveness of a simple internal regenerative fuel preheater for a 20-inch-diameter ram jet. Data obtained at subsonic sea-level conditions indicated that the fuel could be successfully preheated in this manner. The distance the preheater was located downstream of the flame holder was the primary variable affecting the final fuel temperature. Although approximately 5 minutes was required to attain a stable fuel temperature, the rate of fuel-temperature rise was maximum immediately after ignition and useful preheat temperatures ($> 200^{\circ}$ F) were approached within 2 minutes after ignition. The additional pressure loss caused by the introduction of the preheater in the combustion chamber may be considered negligible.

INTRODUCTION

Results of experiments reported in references 1 and 2 indicate that appreciable improvement in ram-jet performance and combustion efficiency can be realized by preheating the fuel. This improvement is the result of a decrease in the time required for the fuel-vaporization process preceding burning. For the investigation described in reference 1, the fuel was either regeneratively heated by being circulated through a copper coil wound around the combustion-chamber shell or was heated by circulation through a steam-heated heat exchanger mounted in the test cell. The use of the steam heat exchanger is merely an experimental technique. Although the external regenerative-heating system is useful in cooling the combustion-chamber shell, it requires an increase in engine frontal area and, if applied to a flight engine, is accompanied by an increase in engine aerodynamic drag. The additional hazard of fuel leaks also contributes to the undesirability of a fuel-preheating system in which the fuel is circulated through a passage around the combustion-chamber shell.

A series of experiments was therefore undertaken to evalute a simple light-weight internal regenerative fuel-preheating system that does not require a change in ram-jet external dimensions and is applicable to aircraft. The study was made at the NACA Lewis laboratory with a 20-inch-diameter ram jet operating at simulated subsonic sea-level flight conditions. The performance of the engine and the internal preheater was investigated for several positions of the preheater in the combustion chamber. At each position, the variation of fuel temperature with time was determined from ignition until stable fuel temperature was reached.

APPARATUS

A schematic diagram of the circular, 20-inch-diameter, steady-flow ram jet used in this investigation is shown in figure 1. All pertinent dimensions are given on the figure. Both the combustion chamber and the exhaust nozzle were water-cooled.

Because A.S.T.M. distillation curves may vary for different batches of the same fuel, the distillation curve for the fuel used (AN-F-28) is shown in figure 2. After passing through the preheater, the fuel was injected in the liquid phase in an upstream direction near the diffuser inlet. The fuel injector consisted of six equally spaced 1/4-inch steel tubes in an 80°-V pattern with the base of the V 5 inches downstream of the diffuser inlet. A total of 68 No. 70 holes were drilled on the upstream side of the fuel bars. These orifices were equally spaced along the six bars; however, no holes were drilled within 2 inches of the diffuser wall.

The flame holder (fig. 3) was a modification of the annular-V type-B burner described in reference 3. This flame holder consisted of two concentric, 30°-V, 3-inch-chord, perforated annuli of 16-inch and 9-inch diameters connected by eight radial gutters. A 30° perforated center cone was supported by two radial gutters extending to the inner annulus. As originally designed, fuel was injected in the V of the flame holder; however, for this investigation, the fuel nozzles were removed. A spark plug was used to ignite the burner.

The regenerative fuel preheater, made of coiled 3/4-inch Inconel tubing, was located in the combustion chamber immediately downstream of the flame holder. The design of this preheater was based on preliminary experiments that indicated the length and the size of fuel-preheating path required for useful preheat temperatures. The preheater weighed 9 pounds and consisted of three convolutions of 16-inch diameter and $2\frac{1}{2}$ convolutions of 9-inch diameter (fig. 4(a)) with adjacent turns spaced $1\frac{1}{2}$ inches apart. Provision was made for varying the distance between the flame holder and the preheater (fig. 1) from 0 to 12 inches. In all positions, the preheater coils were located in the wake of the flame holder (fig. 4(b)). All the fuel passed through the preheater before injection. The inlet and outlet lines to the preheater extended upstream of the flame holder, then through the wall of the diffuser to the outside of the shell.

The diffuser inlet was connected to the outlet of a 500-horsepower, variable-speed, axial-flow blower having a rated delivery of 60,000 cubic feet per minute against a static-pressure rise of 45 inches of water. The ram jet exhausted directly to the atmosphere.

PROCEDURE

The total and static pressures and the indicated temperature measured at the diffuser inlet were used to compute the air flow through the ram jet. From these measurements and the static pressure at the combustion-chamber inlet, the combustion-chamber-inlet velocity was determined. The gas temperature was computed from total and static pressures measured at the nozzle outlet with a water-cooled survey rake. The heat rejected to the shell cooling water amounted to approximately 3 percent of the lower heating value of the fuel and was not included in the evaluation of the combustion efficiency. A rotameter was used to measure the fuel flow. The fuel temperatures were measured at the preheater inlet and outlet. The methods employed in making the calculations are outlined in reference 3.

Fuel temperature at the preheater outlet was recorded at 0.2-minute intervals from the time of ignition until the fuel temperature reached a stable maximum value. The fuel flow and the air flow were maintained approximately constant during this entire period.

The effectiveness of the coils as a preheater was investigated at 0, 4, 8, and 12 inches downstream of the flame-holder trailing edge. At each preheater position the ram jet was operated over a range of fuel-air ratios and at combustion-chamber-inlet velocities from 62 to 95 feet per second.

RESULTS AND DISCUSSION

The data presented herein are characteristic of the installation and should be considered only as an indication of the potentialities of this type of fuel-preheating system. Because a fuel injector with fixed orifices was used, the fuel flow was changed by varying the fuel pressure. Thus the minimum fuel flow at which the ram jet could be operated was determined by the minimum fuel pressure required to keep the preheated fuel from vaporizing in the fuel lines. Additional restriction to the range over which data could be obtained was imposed by the flame-holder burning characteristics.

The range of fuel-air ratios over which the engine could be operated at each preheater position is shown in figure 5. In figure 5 and several succeeding figures, data are presented in range form rather than as actual data points because it was impossible from the data available to separate the effects of combustion-chamber-inlet velocity and fuel-air ratio on the final fuel temperature. The rich fuel-air-ratio limit was established by flame-holder blow-out, whereas the lean limit was due to either flame-holder blow-out or fuel vapor lock. The lean fuel-air-ratio limit can probably be lowered if fuel vapor lock is eliminated. The introduction of the preheater in the combustion chamber and the preheater position had no great effect on the operable fuel-air-ratio range, inasmuch as this range was approximately the same as was obtained with the fuel preheated by an external preheater (reference 4).

For aircraft of short flight duration, the time required for the fuel temperature to rise to a steady value may be an appreciable portion of the total flight time. The rate of fuel-temperature increase from the time of ignition to the time at which a stable fuel temperature is finally attained is therefore important. The variation of fuel temperature with time after ignition and preheater position is presented in figure 6 for several typical operating conditions. Fuel was stored at a temperature of approximately 63° F.

All the data shown in figure 6 can be reduced to a single curve (fig. 7) by plotting the ratio of the temperature rise at any instant to the maximum temperature rise. All the data obtained in this investigation, irrespective of ram-jet operating condition or preheater position, are within ±6 percent of this curve. The variation indicated by the curve in figure 7 may be approximated by a first-order exponential equation of general form $y = 1 - e^{-at}$ having a time constant $t = 1/a$ of 1.17 minutes. An inflection of the curve near the origin indicates the presence of some higher order exponential. Other preheater designs might be expected to follow the same general variation but with a different time constant.

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The data in figure 6 indicate that with given operating conditions an appreciable rise in the final fuel temperature can be achieved by increasing the distance between the flame holder and the preheater from 0 to 8 inches. A further increase from 8 to 12 inches results in little or no gain in the final fuel temperature. A similar result is indicated in figure 8, in which the time to reach a fuel temperature of 200° F from an initial fuel temperature of 63° ±7° is presented as a function of preheater position. (From the results obtained in reference 1, 200° F may be considered a useful preheat temperature.) The data of figure 8 indicate a sharp decrease in the time required to reach 200° F as the distance between the flame holder and the preheater is increased from 0 to 8 inches. The mean time was reduced from 2.4 minutes at zero distance to 1.2 minutes at 8 inches between the flame holder and the preheater. A further increase in this distance from 8 to 12 inches results in an additional reduction in the time of only 0.1 minute. Thus, for all operating conditions, useful preheat temperatures were approached within the first 2 minutes of ignition and the temperature rise attained 99 percent of its final value within 5 minutes. Also from the trends obtained, it is probable that little improvement can be expected from further increase in the distance between the flame holder and the preheater. Further improvement can probably be obtained, however, if the fuel-preheating path is increased by adding more coils to the preheater.

The general range of final fuel temperatures obtained at each preheater position is indicated in figure 9. In addition to being affected by the preheater position, the final fuel temperature is influenced by the engine operating condition. Variation in ram-jet operating conditions resulted in a maximum spread of ±15 percent in the fuel-temperature rise. At the same engine conditions, the final fuel temperature was approximately the same for the preheater in either the 8- or 12-inch position. The difference in spread of the data in figure 9 for these positions is due to differences in ram-jet operating conditions for the data presented.

The heat absorbed per pound of fuel is presented in figure 10 as a function of preheater position. Because the heat absorbed is a function of the final fuel temperature, the values of figure 9 and 10 exhibit the same trend. The amount of heat absorbed per pound of fuel increases sharply as the distance between the flame holder and the preheater is extended. From a mean of 80 Btu per pound of fuel, the amount of heat absorbed by the fuel can be increased to a mean of 120 Btu per pound of fuel, a rise of 50 percent, if the distance between flame holder and preheater is changed from 0 to 12 inches. 1153

An indication of the significance of the heat absorbed by the fuel may be obtained from a comparison with the fuel latent heat of vaporization. The fuel used had a latent heat of vaporization of 145 Btu per pound. The data in figure 10 therefore indicate that a mean of 55 percent of the latent heat of vaporization can be supplied to the fuel at the zero position between the flame holder and the preheater and a mean of 83 percent of the latent heat of vaporization can be supplied to the fuel by the preheater if the distance is increased to 12 inches.

Because the performance of a ram jet is adversely affected by the total-pressure losses the air undergoes in flowing through the engine, the internal pressure losses should be kept as low as possible. The introduction of a preheater in the combustion chamber would contribute toward increasing these pressure losses. An evaluation was therefore made of the effect of the preheater used in this investigation on the combustion-chamber pressure loss. The total-pressure loss across the flame holder alone was 1.5 times the combustion-chamber-inlet dynamic pressure. Because it was believed that the combined pressure loss of the flame holder and the fuel preheater would be a maximum with the preheater 12 inches downstream of the flame holder, the combined loss was determined for only that preheater position. With the preheater located 12 inches downstream of the flame holder, the combined loss across both was only 1.6 times the combustion-chamber-inlet dynamic pressure, an increase of 6.7 percent. This slight increase is negligible when compared with the performance gains possible by preheating the ram-jet fuel (references 1 and 2).

No definite variation of combustion efficiency with preheater position could be established. In general, the combustion efficiency ranged from 60 to 80 percent. Approximately the same range of efficiencies was obtained when this flame holder was used with no internal preheater installed, in which case the fuel was preheated with an external steam-heat exchanger (reference 4).

SUMMARY OF RESULTS

From a subsonic sea-level investigation undertaken to evaluate the effectiveness of a simple internal regenerative fuel preheater for a 20-inch ram jet, the following results were obtained:

1. Between 55 and 83 percent of the latent heat of vaporization could be supplied to the fuel by the preheater.

2. At a given engine condition, the amount of heat added to the fuel and therefore the final fuel temperature increased as the distance between flame holder and preheater was increased from 0 to 8 inches. A further increase to 12 inches resulted in little improvement.

3. For the configuration investigated, approximately 5 minutes of operation after ignition was required before a stable fuel temperature was attained (initial temperature, $63^\circ \pm 7^\circ$). This time did not appear dependent on preheater position or ram-jet operating condition. The rate of fuel-temperature rise was maximum immediately after ignition and a useful preheat temperature of 200° F was approached within 2 minutes.

4. The combustion efficiencies obtained did not appear to be affected by the presence of the preheater nor by the fuel-preheater position.

5. The total-pressure loss across the combustion chamber was increased only 6.7 percent when the preheater was added.

CONCLUSIONS

As a result of this investigation at subsonic sea-level conditions, the following conclusions are indicated: An internal regenerative preheater of the type investigated can be used to preheat fuels to temperatures that result in improved combustion efficiencies. Internal regenerative preheaters may be designed for which the additional internal pressure loss resulting from the introduction of the preheater into the combustion chamber may be considered as negligible. In order to permit operation over a wide range of engine conditions and to prevent fuel vapor lock, the system should employ a variable-orifice fuel injector to permit the fuel pressure to remain above the fuel vapor pressure over a wide range of fuel flows. Because a period of 1 to 2 minutes is required to reach useful preheat temperatures, the application of such a preheater is limited to ram jets having a flight duration greater than this period of time.

The results presented are characteristic of the configuration investigated and other configurations may not give similar performance.

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2. Anon.: Summary Report on Jet Engine Development. .Continental Aviation and Eng. Corp. (Detroit), Aug. 1, 1948. (Air Forces Contract W33-038-ac-13371.) (Available from Central Air Documents Office (Wright-Patterson Air Force Base, Ohio), under ATI No. 52077.)

3. Perchonok, Eugene, Wilcox, Fred A., and Sterbentz, William H.: Preliminary Development and Performance Investigation of a 20-Inch Steady-Flow Ram Jet. NACA ACR E6D05, 1946.

4. Sterbentz, W. H., Perchonok, E., and Wilcox, F. A.: Investigation of Effects of Several Fuel-Injection Locations on Operational Performance of a 20-Inch Ram Jet. NACA RM E7L02, 1948.

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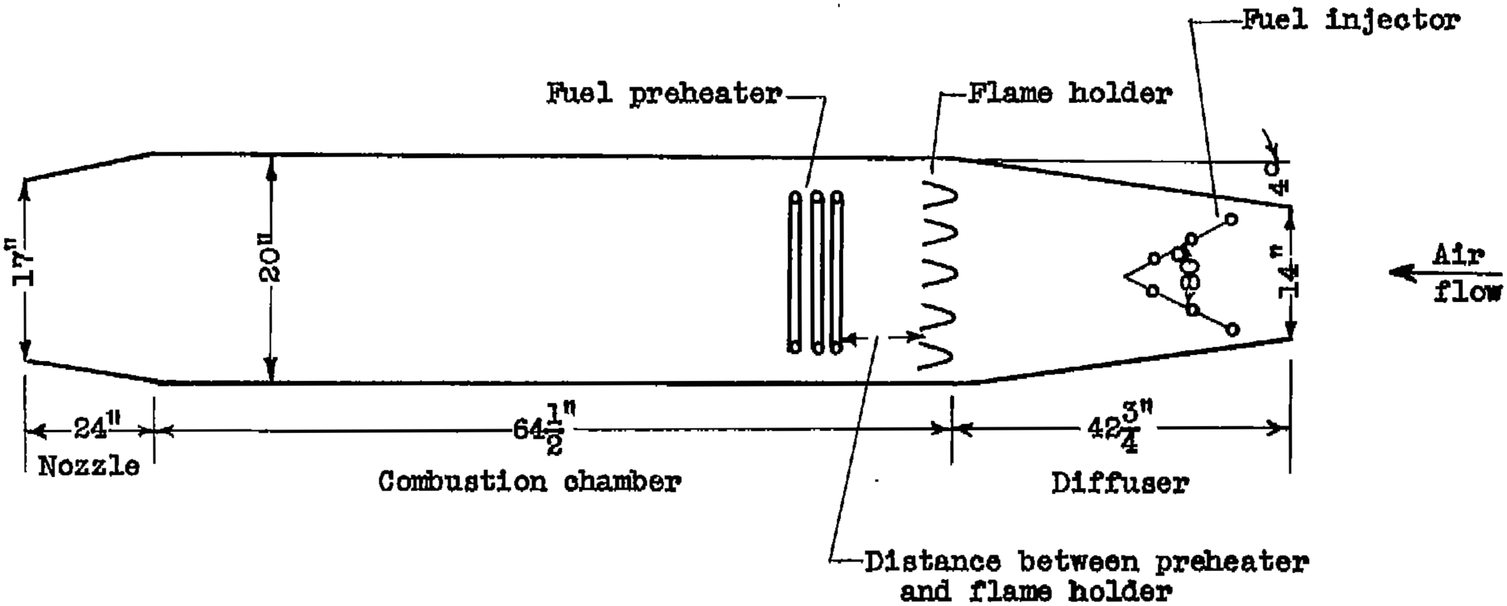

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Figure 1. - Schematic diagram of 20-inch-diameter ram jet.

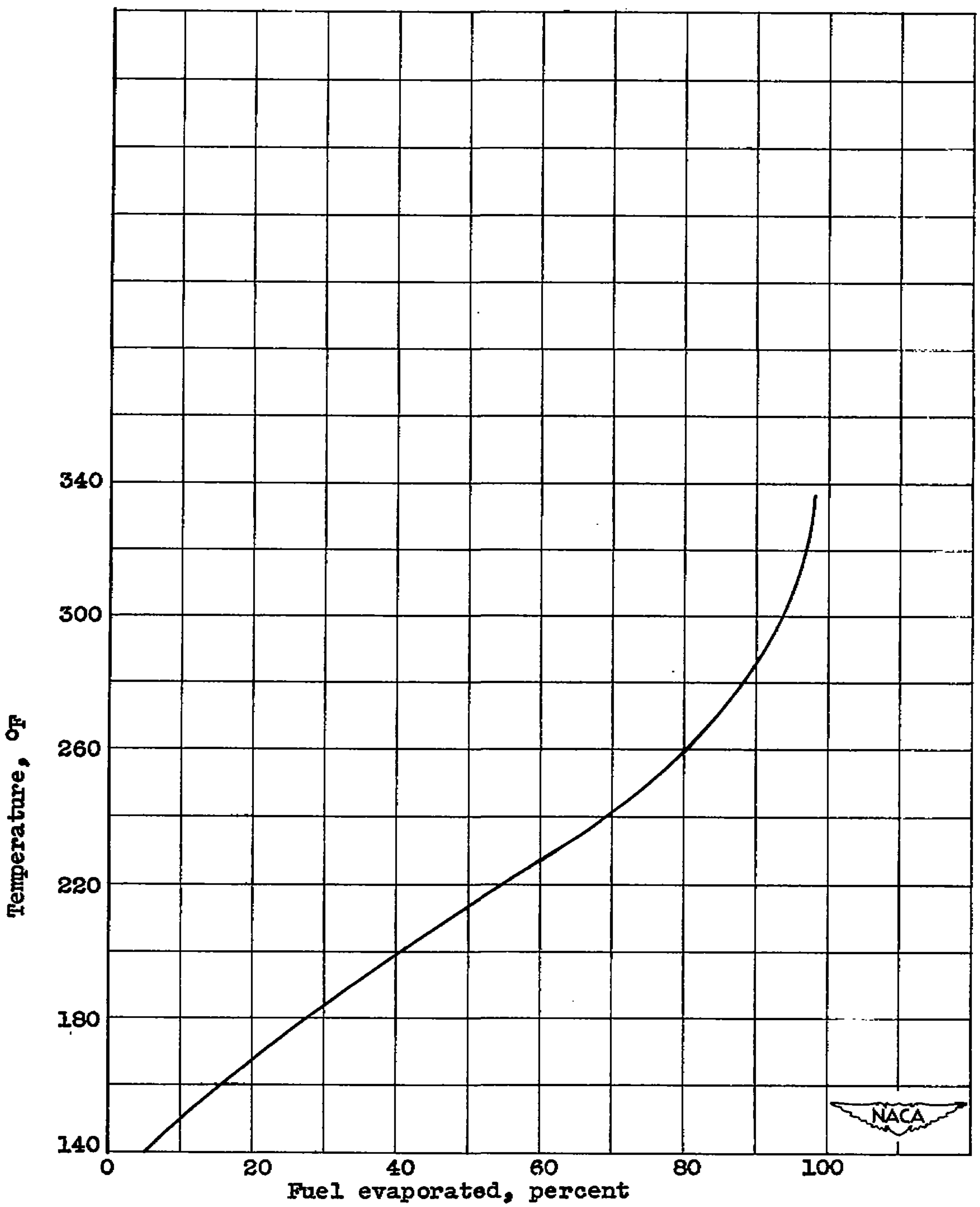


Figure 2. - A.S.T.M. distillation curve for AN-F-28 fuel used in 20-inch-diameter ram jet.

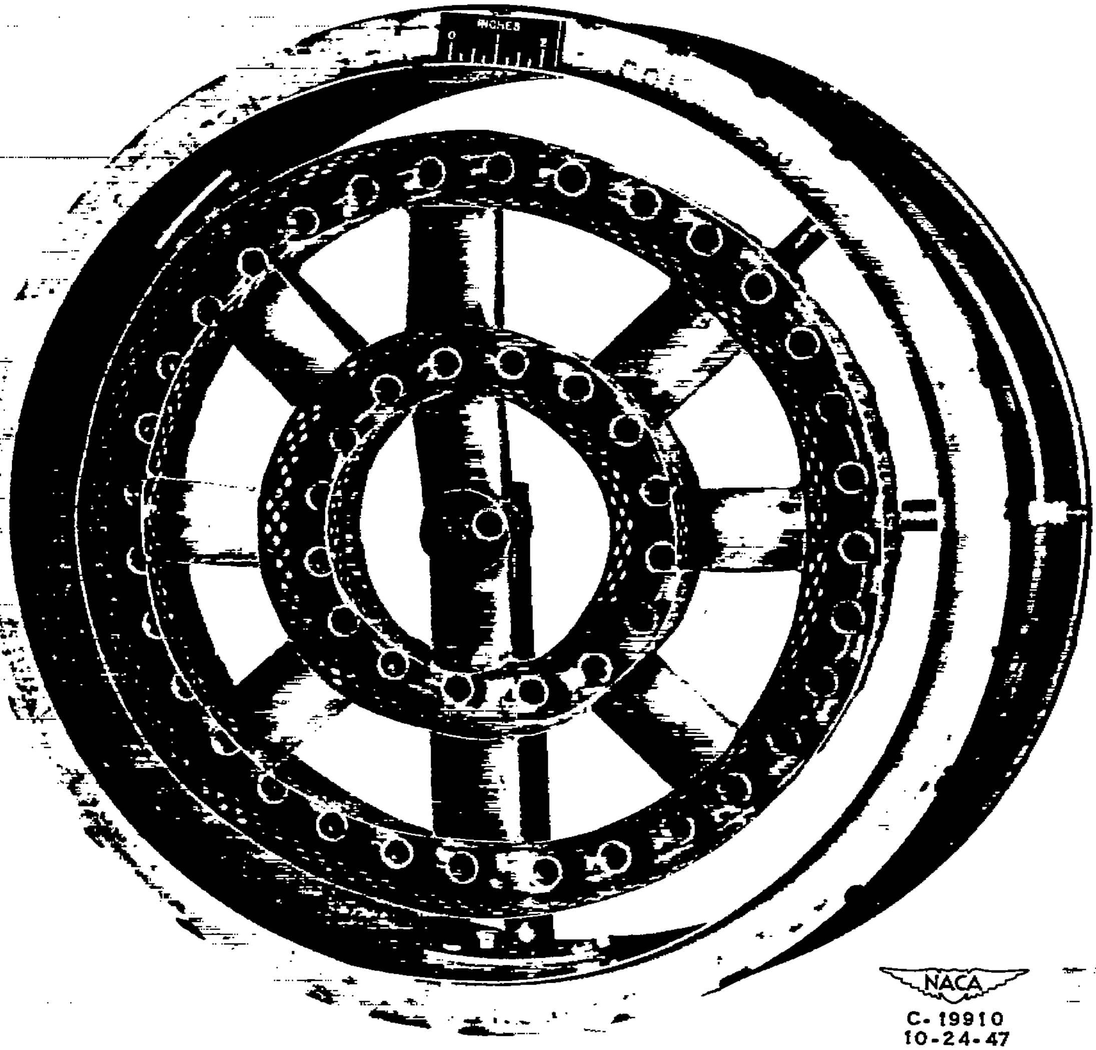
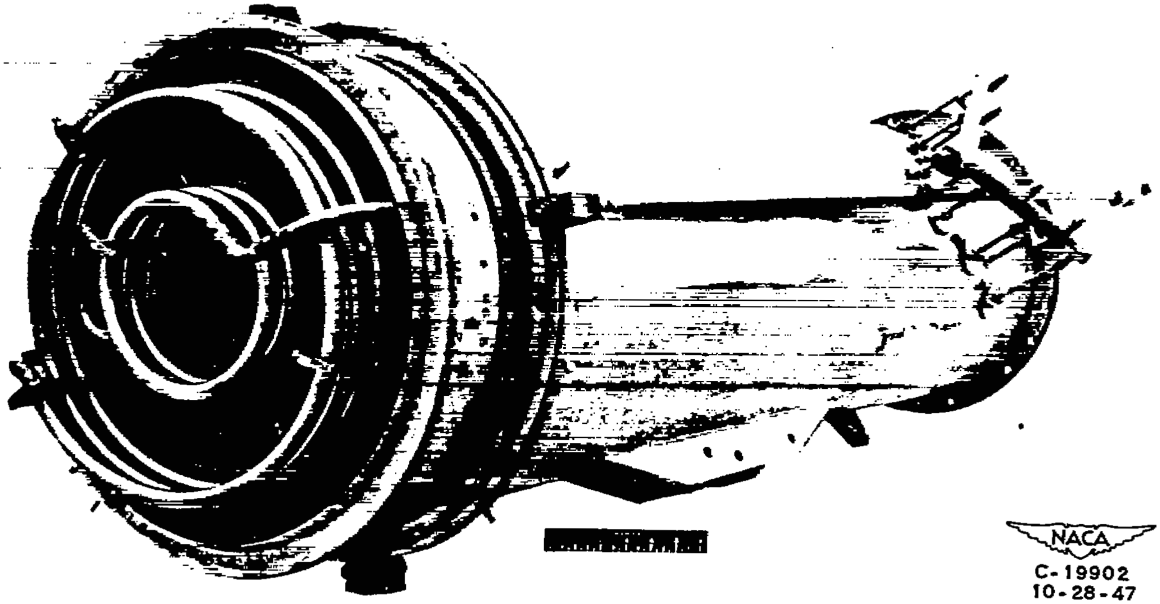
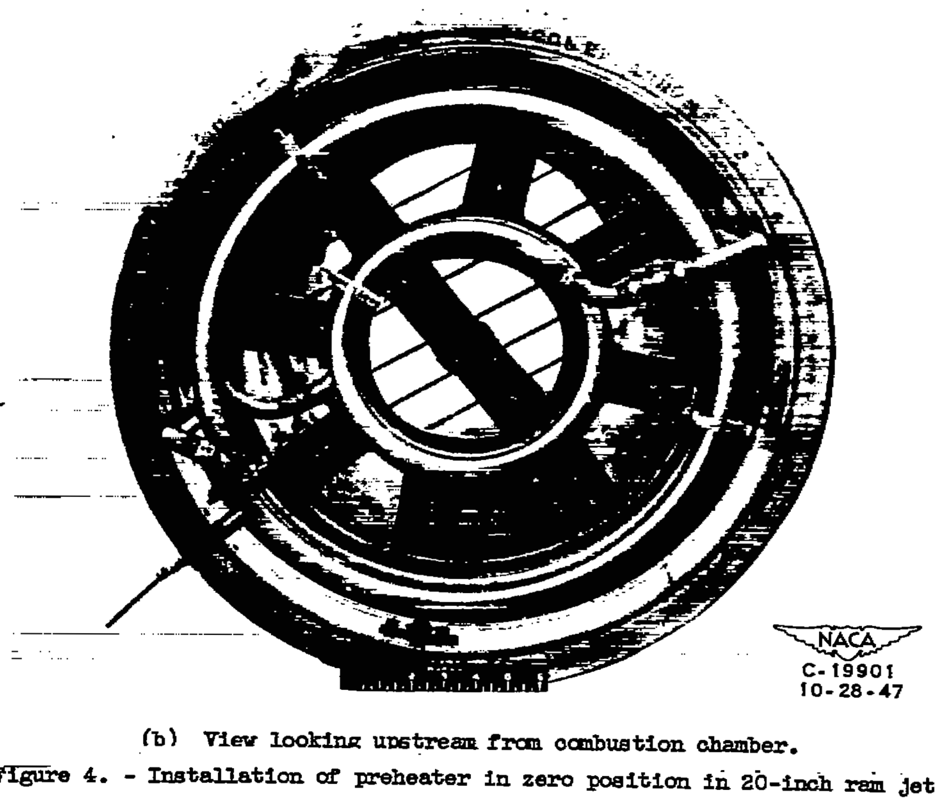


Figure 3. - View of flame holder looking upstream from combustion chamber.



(a) Three-quarter side view.



(b) View looking upstream from combustion chamber.

Figure 4. - Installation of preheater in zero position in 20-inch ram jet.

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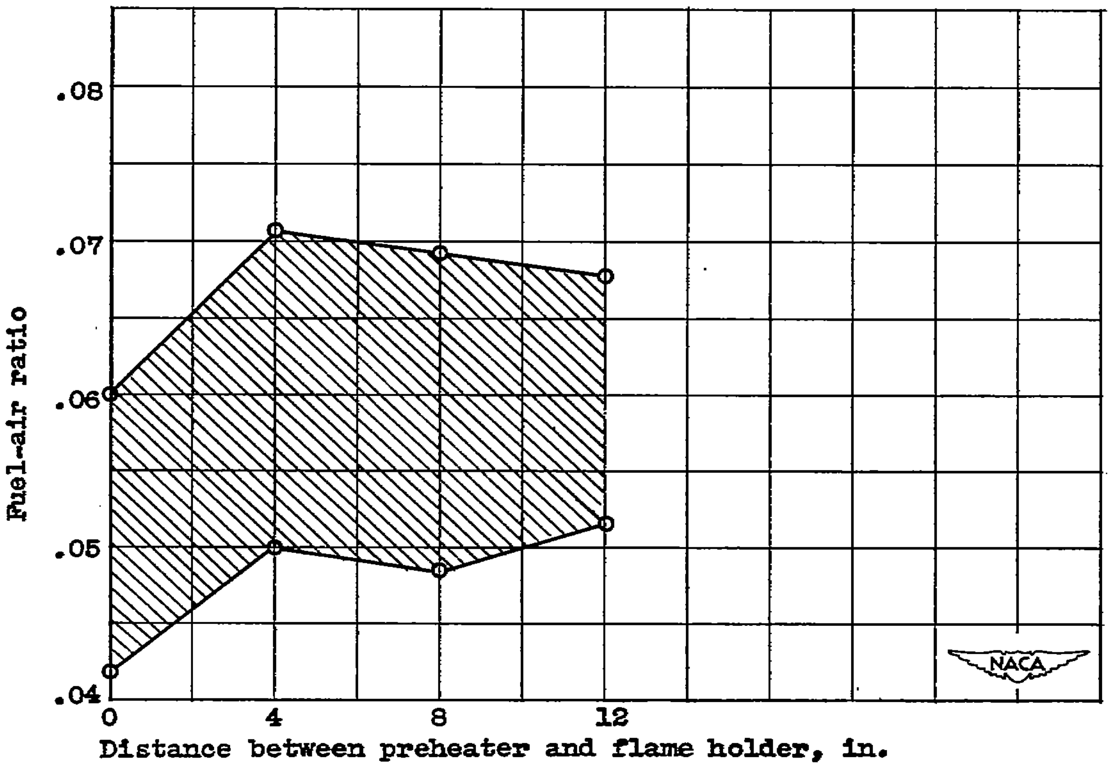

Figure 5. - Effect of preheater position on operable fuel-air-ratio range.

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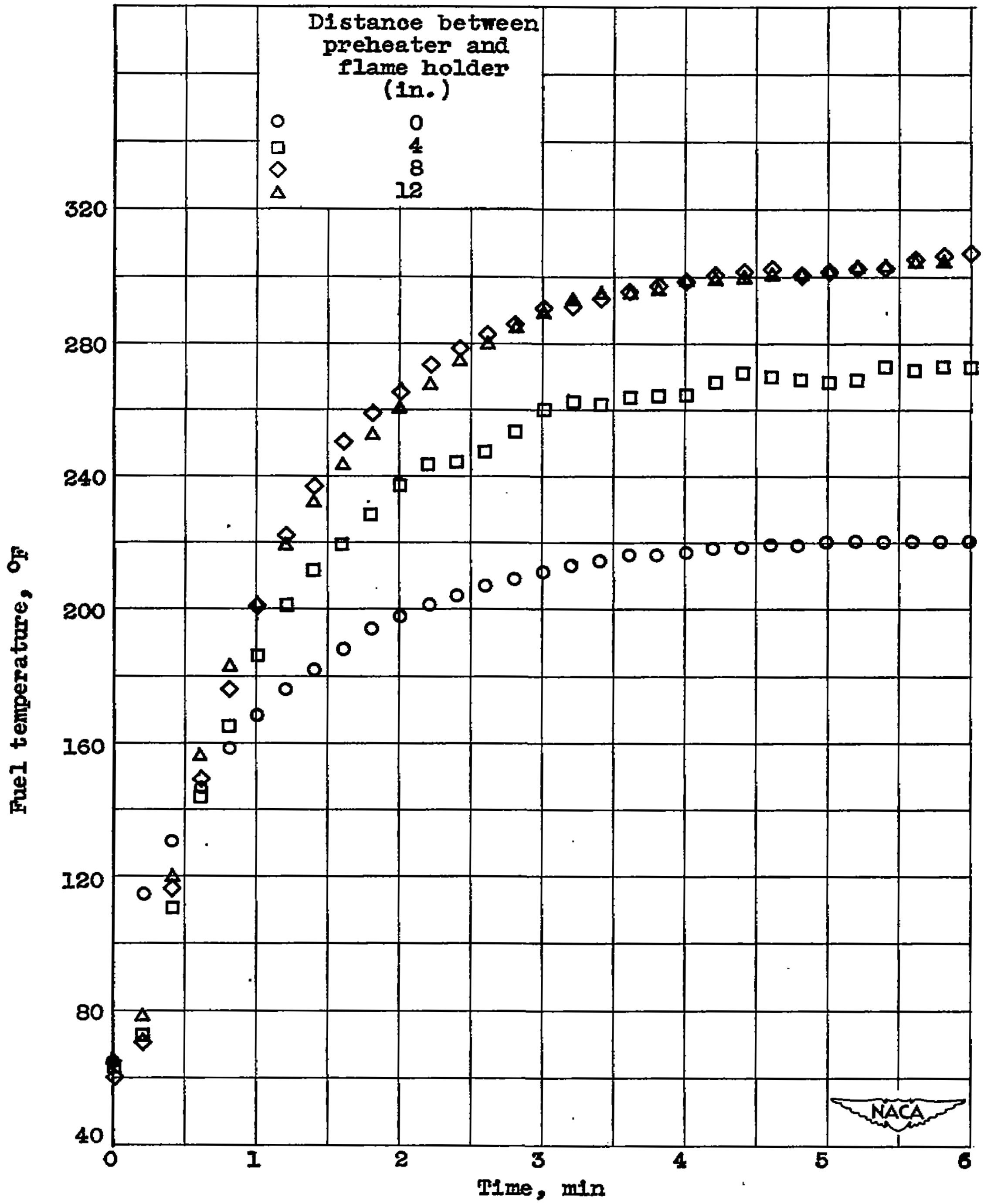

(a) Fuel flow, 2200 pounds per hour; fuel-air ratio, 0.058 ±0.001.

Figure 6. - Effect of preheater position on fuel-heating rate.

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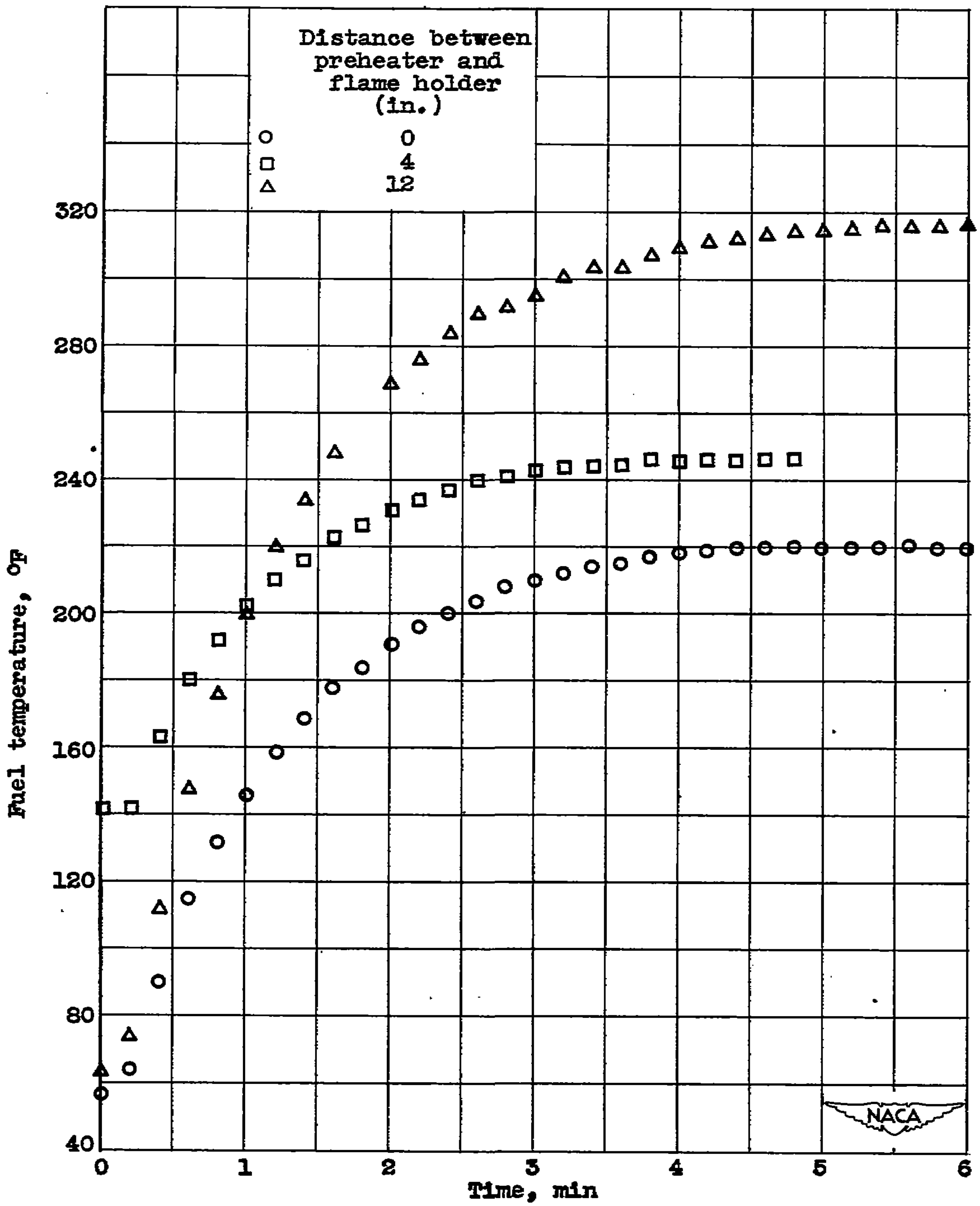

(b) Fuel flow, 2600 pounds per hour; fuel-air ratio, 0.054 ±0.001.

Figure 6. - Continued. Effect of preheater position on fuel-heating rate.

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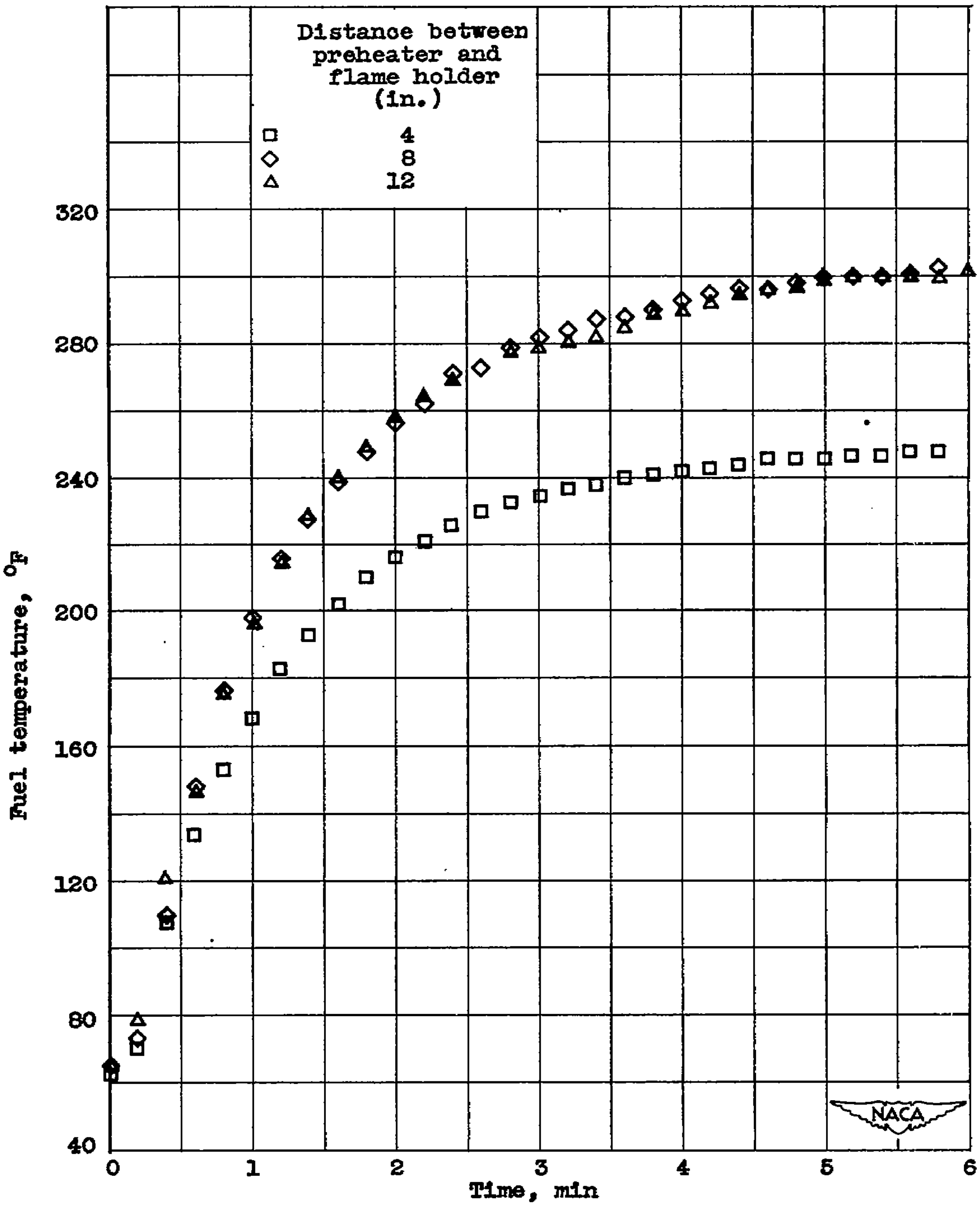

(c) Fuel flow, 2600 pounds per hour; fuel-air ratio, 0.061 ±0.001.

Figure 6. - Concluded. Effect of preheater position on fuel-heating rate.

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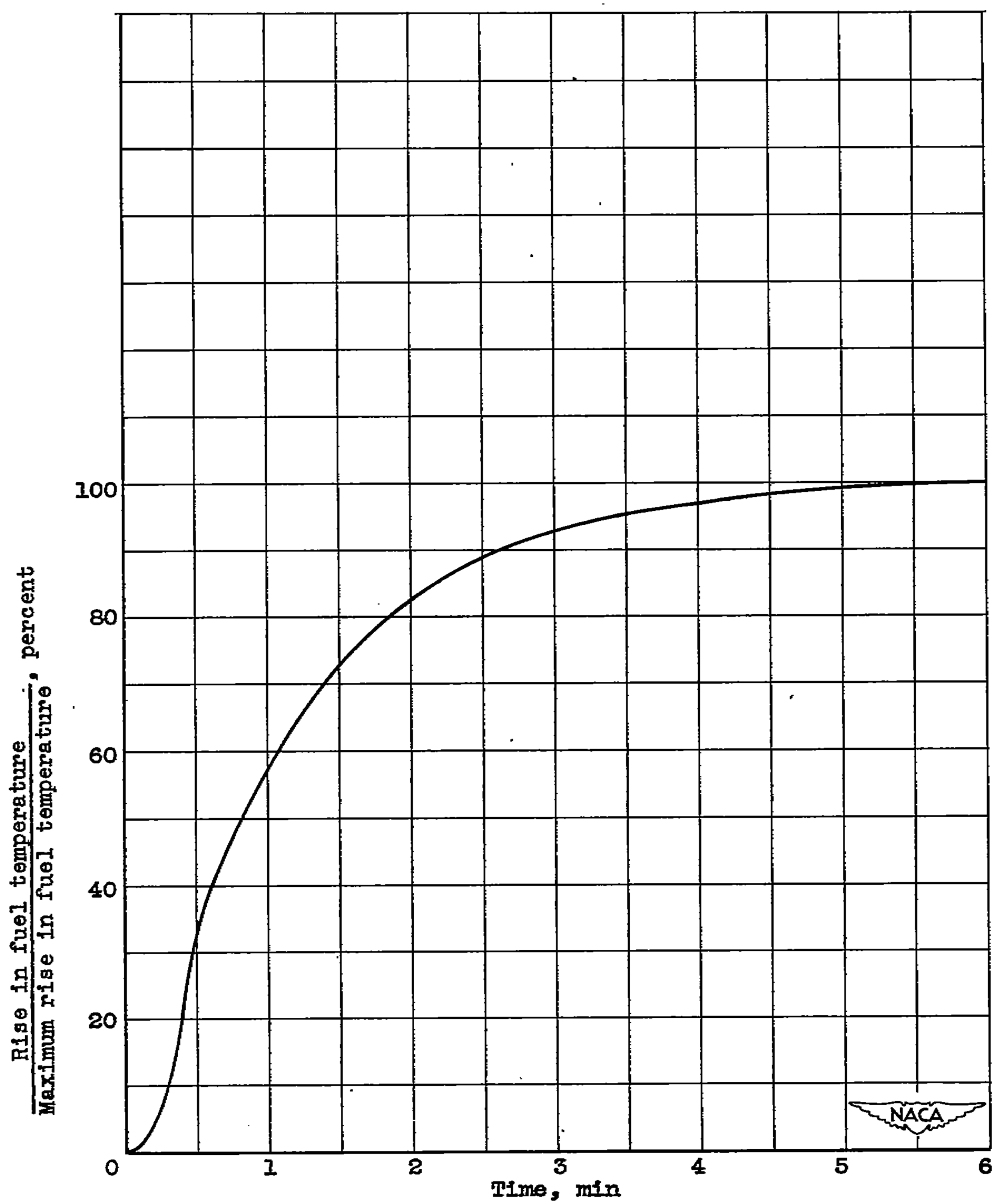

Figure 7. - Variation of ratio between rise in fuel temperature to maximum rise in fuel temperature as function of heating time. (All data are within ± 6 percent of curve.)

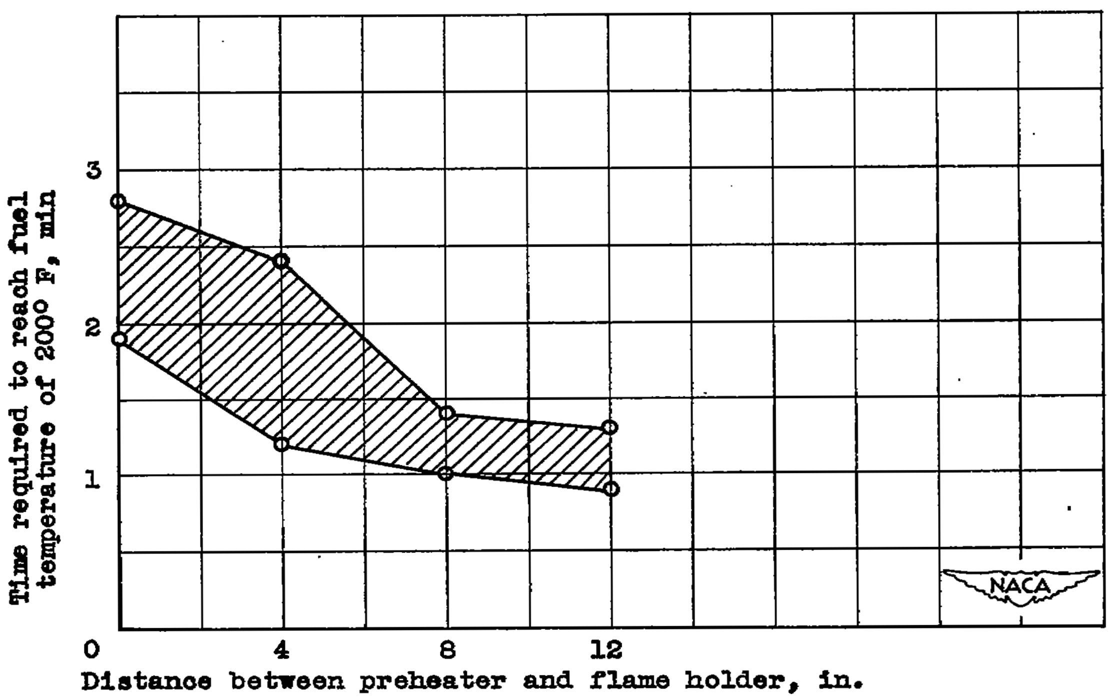

Figure 8. - Effect of preheater position on time required to attain fuel temperature of 200° F. Initial temperature, 63° ±7° F.

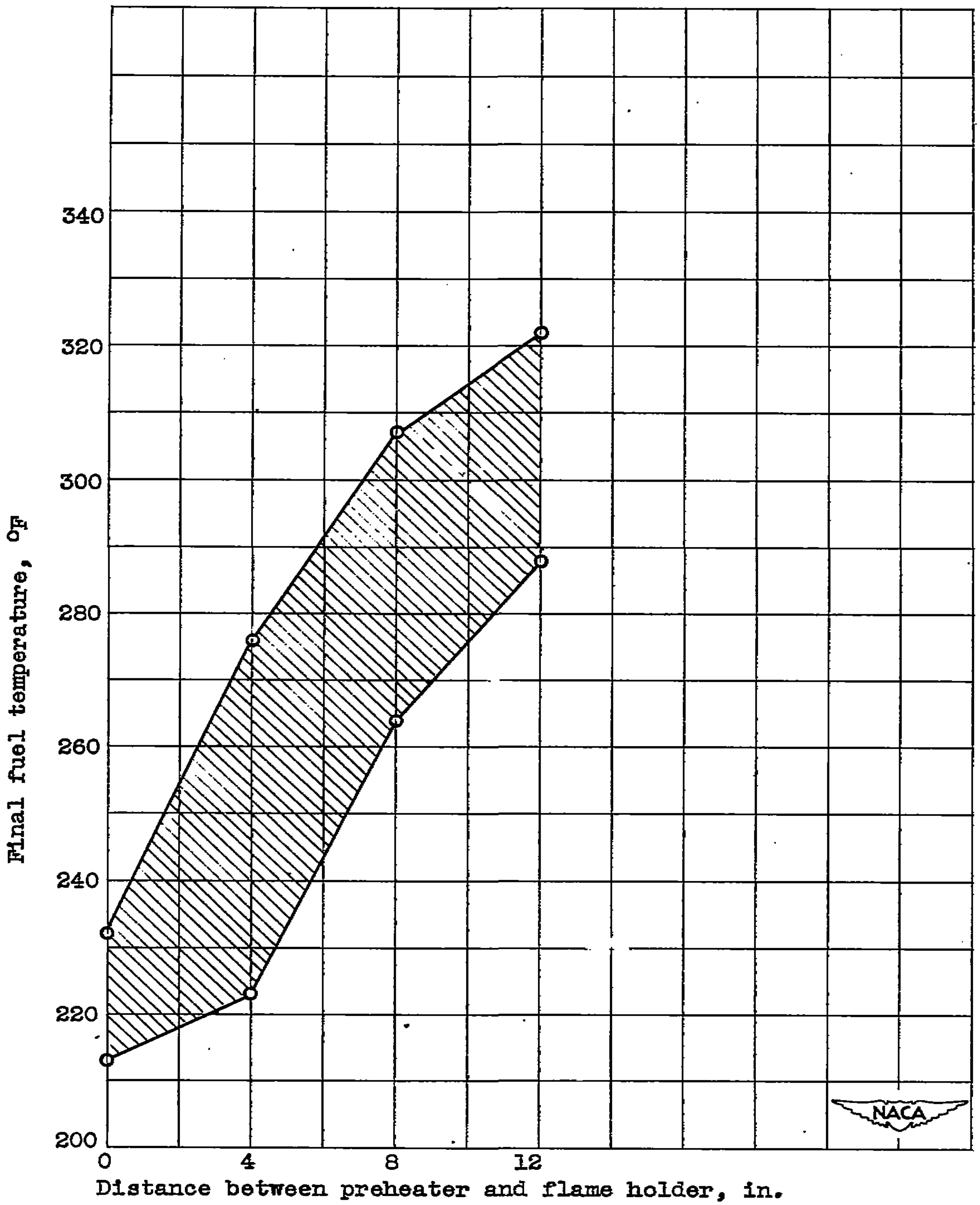

Figure 9. - Effect of preheater position on range of final fuel temperature.

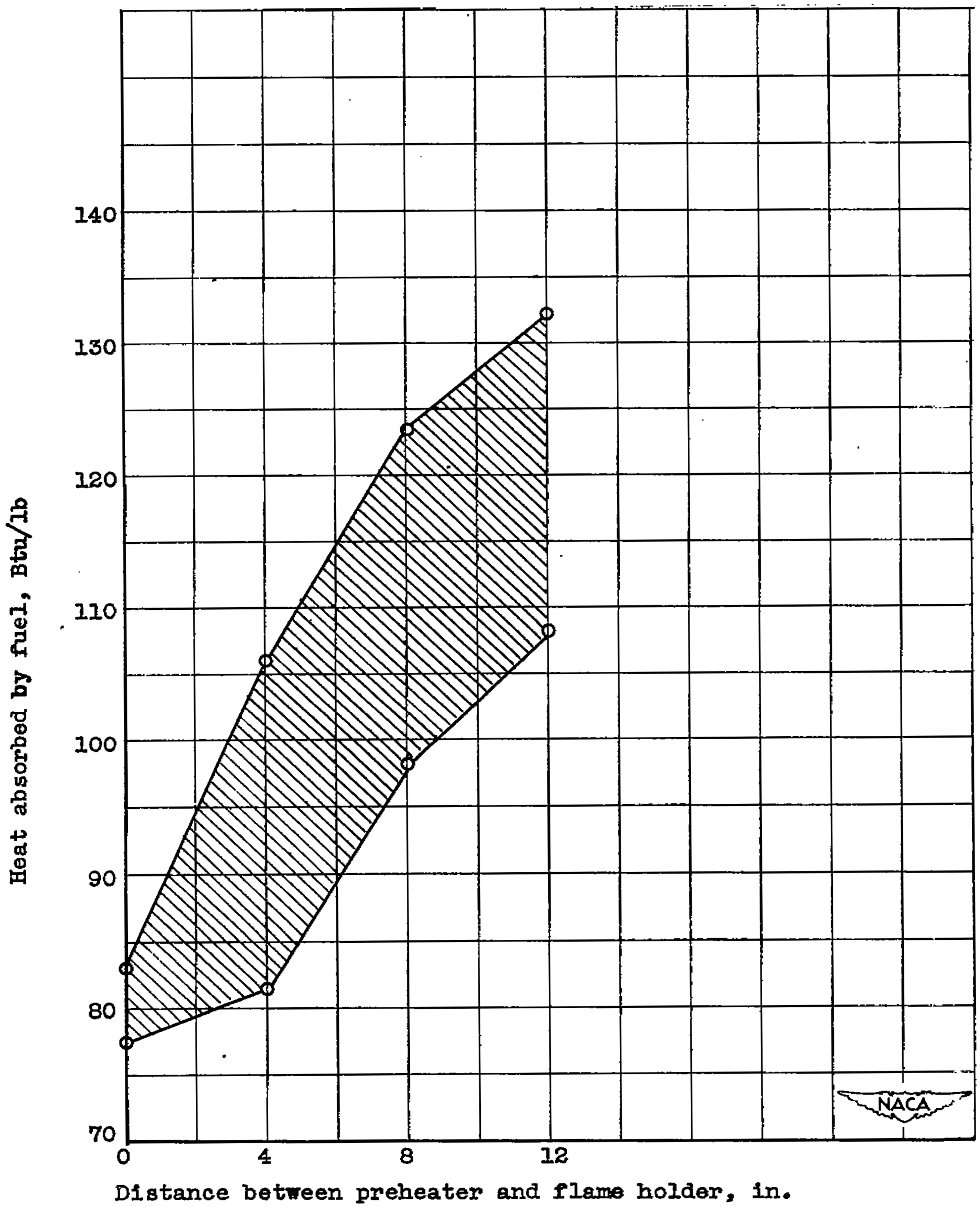

Figure 10. - Effect of preheater position on heat absorbed by fuel.

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